

CURRENT SENSOR AND CURRENT DETECTION UNIT
USING THE SAME

BACKGROUND OF THE INVENTION

5 Field of the Invention

This invention relates to a current sensor for detecting an electric current flowing through a signal line. More particularly, the present invention relates to a high sensitivity current sensor for
10 detecting an electric current by using a magneto-impedance device or a flux-gate sensor whose magnetic permeability changes in response to the external magnetic field and also to a current detection unit using such a current sensor.

15 Related Background Art

Conventionally, current transformers and hall devices are used as current sensors for detecting an electric current. The current sensor market is expected to expand as electric automobiles have come
20 on the scene and power monitoring for the purpose of power saving has been promoted in recent years. Current detecting operations have been increasingly ramified as a result of advancement of current management using networks and accordingly the
25 detection range of current detecting operations has been lowered. As a result, there is an increasing demand for highly sensitive current sensors. In short,

as the detection range of current detecting operations lowers, the magnetic sensors to be used for the detecting operations are required to show a higher S/N ratio.

5 In such a trend, the use of magneto-impedance devices and flux-gate sensors that are more sensitive than conventional hall devices is highly promising. Then, it is important to realize a compact current sensor by using such a sensitive device.

10 FIG. 9 of the accompanying drawings shows a known typical current sensor that comprises a magnetic circuit by a C-shaped magnetic core 102 turned around an electric wire 100 and a hall device 104 arranged in the gap of the magnetic core 102. The
15 hall device 104 does not show saturation and hence can operate in a strong magnetic field because it is not ferromagnetic.

 However, magneto-impedance devices and flux-gate sensors are formed by using a ferromagnetic substance
20 and hence require to be used within a non-saturation range because they show magnetic saturation. In other words, when a magnetic circuit is configured by using a magneto-impedance device or a flux-gate sensor like the one using a hall device, the magnetic field of
25 the gap becomes too strong and magnetic saturation appears easily if an electric current in the order of amperes is detected. Thus, a circuit configuration

like that of a circuit using a hall device is not feasible when a magneto-impedance device or a flux-gate sensor is involved.

5 Additionally, it is necessary for a high
sensitivity magnetic sensor, when it is ferromagnetic,
to confine the magnetic field detection range to
about ± 15 gaussses (± 1.5 milliteslas or mT) if a wide
detection range can be realized by using negative
feedback or the like for the drive circuit. In other
10 words, when the magnetic field from an electric wire
is to be detected directly, the distance needs to be
adjusted so that intensity of the magnetic field may
be found within the above detection range.

15 However, the current sensor may confront
dimensional limitations if the combination of a
device and an electric wire is switched from one to
another depending on the required current detection
range. Then, the applicability of such a current
sensor will also be limited. Particularly, a current
20 sensor adapted to large electric currents may need to
have large dimensions.

25 Furthermore, the magnetic fields produced from
some electric parts other than the target electric
wire that may include power transformers need to be
handled appropriately. If a magnetic shield is used,
conditions for using such a shield need to be
considered so that the shield may not influence the

magnetic field produced from the electric wire nor be magnetically saturated.

SUMMARY OF THE INVENTION

5 It is, therefore, an object of the present invention to provide a current sensor and a current detection unit using it that do not have large dimensions but are adapted to highly sensitively detect an electric current and can be manufactured
10 with ease at low cost.

 According to the invention, the above object is achieved by providing a current sensor using a magnetic detection device having a magnetic body adapted to allow high frequency currents to directly
15 flow through it and change its magnetic permeability in response to the external magnetic field, said sensor comprising:

 parallel electric wire sections of a pair of electric wires arranged in parallel with each other
20 and adapted to flow respective electric currents of the same intensity in directions opposite to each other; and

 said magnetic detection device arranged on a prolonged line connecting the center axes of said
25 parallel electric wire sections; wherein

 said magnetic detection device has a magnetic field detecting direction rectangular relative to the

prolonged line and is adapted to detect the difference between the magnetic field formed by the parallel electric wire section located close to the magnetic detection device and the magnetic field
5 formed by the parallel electric wire section located remote from the magnetic detection device and directed oppositely relative to the former magnetic field in order to detect the intensity of the electric currents flowing through said parallel
10 electric wire sections.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic perspective view of an embodiment of current sensor according to the
15 invention;

FIGS. 2A and 2B are schematic plan views of the embodiment of FIG. 1;

FIG. 3 is a schematic perspective view of an embodiment of current detection unit realized by
20 using a current sensor as shown in FIG. 1;

FIG. 4 is a schematic perspective view of the current sensor used in an experiment for evaluating the present invention;

FIG. 5 is a schematic circuit diagram of the drive circuit used in an experiment for evaluating
25 the present invention;

FIG. 6 is a graph showing the current detection

characteristic of the current sensor obtained as a result of the experiment for evaluating the present invention;

FIG. 7 is a schematic circuit diagram of another drive circuit;

FIG. 8 is a schematic perspective view of another embodiment of current detection unit; and

FIG. 9 is a schematic perspective view of a current sensor comprising a conventional hall device.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

Now, the present invention will be described in greater detail by referring to the accompanying drawings that illustrate preferred embodiments of the invention. FIG. 1 is a schematic perspective view of an embodiment of current sensor according to the invention, illustrating the relative position relationship between the magnetic detection device and the electric wire for detecting the electric current flowing through it.

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Referring to FIG. 1, magnetic detection device 10 is a magneto-impedance device (to be referred to as MI device hereinafter) that is adapted to directly flow a high frequency current to a magnetic body (magnetic thin film) 14 formed on a non-magnetic substrate 12 and changes its impedance in response to the external magnetic field. For the magnetic

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detection device 10, the MI device may alternatively be formed not by using a thin film but by using an amorphous wire. Still alternatively, it may be adapted to operate as flux-gate sensor adapted to
5 take out an output from a coil arranged near or wound around the magnetic detection device 10.

As shown in FIG. 1, the MI device is realized by folding the magnetic thin film 14 to show a zigzag pattern on the non-magnetic substrate 12 such as
10 glass and provided at the opposite ends with electrodes 16a, 16b to which a high frequency electric current can be applied. The magnetic field detecting direction of the MI device runs in parallel with the longitudinal direction of the pattern of the
15 magnetic thin film 14 as indicated by arrow Hi.

The target electric wire 20 whose magnetic field is to be detected by the magnetic detection device 10 has parallel electric wire sections 20a, 20b produced by bending the electric wire 20 at an end of the
20 parallel electric wire section 20a and the corresponding end of the parallel electric wire section 20b. The prolonged line connecting the center axes of the parallel electric wire sections 20a, 20b extends in X-direction and the magnetic detection
25 device 10 is arranged on the prolonged line. The magnetic field detecting direction and the direction in which the parallel electric wire sections are

arranged are substantially rectangular relative to each other.

FIG. 2A is a schematic plan view of the magnetic detection device when the device is viewed from above in terms of the viewpoint of FIG. 1. Assume that the parallel electric wire section 20a located close to the magnetic detection device 10 and the parallel electric wire section 20b located remote from the magnetic detection device 10 are separated from each other by gap d and the distance between the center of the magnetic body 14 that is the detecting section of the device and the center of the parallel electric wire section 20a close to the magnetic detection device 10 is s.

The magnetic field H at the magnetic detection device 10 is expressed by the difference between the inverse functions of the respective distances from the parallel electric wire sections. If the electric wire 20 is assumed to have an infinite length for the purpose of simplicity, the magnetic field H is expressed by the formula below.

$$H = (1 / s) - (1 / (s + d)) = (1 \times d) / s (s + d)$$

FIG. 2B illustrates the relationship between the magnetic field and the distance. The upper solid curve represents the magnetic field due to the parallel electric wire section 20a and the lower solid curve represents the magnetic field due to the

parallel electric wire section 20b. The broken curve represents the synthetic magnetic field obtained from the magnetic field due to the parallel electric wire section 20a and the magnetic field due to the
5 parallel electric wire section 20b.

The direction of the electric current flowing through the parallel electric wire section 20b located remote from the magnetic detection device 10 is inverse relative to the direction of the electric
10 current flowing through the parallel electric wire section 20a located close to the magnetic detection device 10 so that the synthesized magnetic field relative to the magnetic detection device 10 can be weakened as a function of distance d as indicted by
15 the broken curve in FIG. 2B. In other words, while a conventional current sensor is separated from the target signal line by a large distance when it detects an intense magnetic field due to a large electric current, the magnetic detection device of a
20 current sensor according to the invention can be brought close to the target signal line when the latter is made to have two parallel electric wire sections through which respective electric currents flow in opposite directions and the gap d between the
25 two parallel electric wire sections is reduced.

More specifically, the magnetic field is attenuated to $1/2$ of the magnetic field observed when

the target signal line is a single line if $d = s$.
Similarly, the magnetic field is attenuated to $1/3$ of
the magnetic field observed when the target signal
line is a single line if $d = s/2$. When the required
5 effect is taken into consideration, it may be
desirable to make d smaller than s for the basic
configuration of the current sensor.

From the viewpoint of applicability of a current
sensor, it is possible to apply a magnetic field
10 necessary for the device section without changing the
external dimensions of the current sensor by
selecting appropriate values for s and d depending on
the requirements of the specifications that need to
be met for the electric current to be detected. In
15 other words, a current sensor according to the
invention can be adapted to various products whose
requirements of the specifications are diverse only
by changing the positional relationship of the
parallel electric wire sections as a function of the
20 specifications of the product without changing both
the external dimensions of the product and the
requirements for the circuit.

In the case of a highly sensitive magnetic
sensor, the magnetic field detection range of the
25 current sensor is about ± 3 gaussses ($\pm 300 \mu\text{T}$) where a
good linearity is provided, which can be expanded to
a five times wider range by using a feedback circuit.

Thus, the upper limit of range may be about ± 15 gaussses (± 1.5 mT). Therefore, the gap between the two parallel electric wire sections and the distance from the magnetic detection device need to be adjusted so
5 that the magnetic field detection range may be found within this range and the maximum current metering range may not exceed these values.

While a single magnetic detection device is used, a magnetic shield member needs to be used to shield
10 the device against any external magnetic field, the magnetic shield can disturb the magnetic field produced by the electric current if the shield member is not arranged at appropriate position.

While the magnetic field of an electric wire
15 shows a circular contour that is centered at the axis thereof, the tendency of absorbing the magnetic flux of a shield member is intensified when the shield member formed by a magnetic body is located within the circle. Therefore, the wall surface of the shield
20 member needs to be separated from the electric wire by a distance at least greater than the distance between the electric wire and the detecting section of the device. This will be described by referring to FIG. 2A. When a magnetic shield member is found in
25 the circular magnetic fields 22, 24, which are formed respectively by the parallel electric wire sections 20a, 20b and pass through the magnetic detection

device 10, the tendency that the magnetic flux passes through the shield member is intensified, and the metering by the magnetic detection device 10 is largely influenced by the magnetic field disturbance. Therefore, it is important that the magnetic shield member 26 that surrounds the measuring system does not intersect the circle having a half diameter of $s + d$, as shown in FIG. 2A.

Now, the structure of a compact current sensor according to the invention will be described by taking productivity into consideration. FIG. 3 is a schematic perspective view of an embodiment of current detection unit realized by mounting a magnetic detection device as shown in FIG. 1 on a flat circuit substrate 30.

Referring to FIG. 3, the magnetic detection device 10 is mounted with other electric parts on the circuit substrate 30 in such a way that the side where the electrodes 16a, 16b are arranged faces downward. In FIG. 3, reference symbol 37 denotes a drive circuit IC for applying a high frequency current to the magnetic body 14 and taking out the sensor output as will be described in greater detail hereinafter. The electric wire 32 is formed by punching out and bending an electrically conductive material having a low electric resistance such as copper. The electric wire 32 has parallel electric

wire sections 32a, 32b, which are separated by a gap that is broadened at the open ends of the parallel electric wire sections 32a, 32b, which open ends operate as terminals. With this structure, the
5 outermost dimensions of the terminals can be made common to a series of products so long as the gap separating the open ends are held sufficiently wide if the gap between the parallel electric wire sections is varied depending on the specifications of
10 product and according to the electric current to be detected.

While the electric wire of FIG. 1 has a circular cross section, the electric wire 32 of FIG. 3 may show a rectangular cross section. Rather, the
15 electric wire 32 may preferably have a rectangular cross section because the magnetic detection device 10 and the electric wire can be brought closer to each other when the electric wire has such a cross section. Additionally, while the magnetic field
20 applied to the magnetic detection device has an arc-shaped contour when the electric wire has a circular cross section, the magnetic field has a contour that is extended in the magnetic field detecting direction when the electric wire has a rectangular cross
25 section to advantageously make the distribution of the magnetic field applied to the magnetic detection device linear and stable. It is preferably that the

width of the rectangular cross section of the parallel electric wire sections 32a, 32b is greater than the length of the magnetic body 14 that operates as detecting section of the device in the magnetic
5 field detecting direction.

The electric wire 32 is arranged through a through hole or a notch 30a formed in the circuit substrate 30 and the magnetic detection device 10 is arranged in the direction in which the axes of the
10 parallel electric wire sections 32a, 32b are arranged. With this structure, a current detection unit can be assembled with ease by way of a step of arranging an electric wire 32 so as to stand through a base member 34, a step of putting a circuit substrate 30 carrying
15 thereon a magnetic detection device 10 on the base member 34 and a step of covering the above components with a magnetic shield member 36.

Additionally, current sensors require mass production and hence the above-described assembling
20 process is suited to manufacturing current sensors. Furthermore, current sensors that can cover a considerably wide spectrum of electric current can be produced simply by rigidly securing the circuit substrate 30, the magnetic shield member 36 and the
25 center axis 38 of the electric wire 32 relative to each other and changing the gap d between the parallel electric wire sections 32a and 32b. This

arrangement is free from cumbersome operations of preparing and selecting different peripheral parts depending on the specifications adapted to a given electric current range.

5 Now, the evaluation outcome of current detection units according to the invention will be described below. FIG. 4 is a schematic perspective view of the current sensor used in an experiment for evaluating the present invention. In the illustrated current
10 sensor, an MI device 42 was formed from a strip of magnetic thin film on a non-magnetic substrate 40 and a spiral coil 44 was formed thereon. The opposite ends of the MI device 42 were connected to electrodes 46a, 46b.

15 The spiral coil 44 included a left side coil and a right side coil that were connected to each other. The inner end of the left side coil was connected to the electrode 46b, while the inner end of the right side coil was connected to the other electrode 46b.
20 Thus, as the MI device 42 was electrically energized, the output could be taken out from the coil 44.

 FIG. 5 is a schematic circuit diagram of the drive circuit of the current sensor. In this instance, a high frequency electric current was applied to the
25 magnetic body 14 and the change in the permeability was taken out as coil output. Firstly, a high frequency electric current was applied to the MI

device 42 uniformly in terms of positive and negative
from a pulse oscillator 50 by way of a buffer 52 and
an electric current adjusting resistor 54. The output
of the coil 44 changed in response to the external
5 magnetic field and the peaks of the change at the
positive and negative sides were taken out
respectively by means of detection circuits 56p, 56m
and the signals of the middle points were output
respectively from resistors 58p, 58m so that the
10 sensor output Eout could be obtained by amplifying
the signal by means of amplifier 60.

Although not shown, it is possible to provide a
feed back circuit configuration so as to improve the
accuracy and broaden the current detection range by
15 winding a solenoid-shaped coil around the magnetic
detection device along the magnetic field detecting
direction and connecting the output Eout to the
ground by way of a feedback adjusting resistor.

As for the dimensions of the electric wire, a U-
20 shaped electric wire was formed by using a copper
wire having a cross section that is 5 mm wide and 1.5
mm thick and separating the parallel electric wire
sections by a gap of 3 mm and the electric wire
section located close to magnetic detection device
25 and the detection axis of the magnetic detection
device by a distance of 4.5 mm (the height of the
electric wire was 21.5 mm). The drive circuit of FIG.

5 was driven by a supply voltage of 5V and the gain of the amplifier 60 was selected to be 100 times. The current sensor was enclosed in a shield of Permalloy.

FIG. 6 is a graph showing the current detection
5 characteristic of the current sensor for DC $\pm 15A$. It will be seen that an excellent linearity was obtained. When computed back from the inclination of the line and the magnetic field detecting characteristics of the magnetic detection device, it was found that the
10 magnetic field was 0.08 gauss (8 μT) per 1A. Assuming that the two parallel electric wire sections have an infinite length and that respective electric currents flow in opposite directions, the magnetic field will be 0.178 gauss (17.8 μT) when determined
15 by computation. However, the actual magnetic field was less than a half of it because of the fact that the electric wire had a definite length and a magnetic circuit was formed through the shield. If a current detection system is constituted by means of a
20 similar arrangement, using a single line having an infinite length without a shield, the magnetic detection device and the electric wire will have to be separated by a distance of 25 mm. Therefore, the above-described arrangement can reduce the distance
25 between the magnetic detection device and the electric wire to 1/4 or less, which will be very significant when downsizing the current sensor.

FIG. 7 is a schematic circuit diagram of another drive circuit. This circuit is designed to apply a high frequency current to the magnetic body 14 and take out the change in the impedance thereof. While a
5 current sensor as shown in FIG. 4 is also used, the spiral coil 44 is used for a bias magnetic field and the sensor output is taken out as the change in the voltage amplitude relative to the high frequency current for energizing the MI device 42. In FIG. 7,
10 reference symbol 62 denotes an oscillation circuit for electrically energizing the MI device 42 by means of a high frequency current by way of buffer 64 and an electric current adjusting resistor 66.

A DC bias current I_b is applied to the spiral
15 coil 44. The change in the magnetic field due to the high frequency current appears as a change in the voltage amplitude at the opposite ends of the MI device 42 so that the sensor output is obtained by causing the output to pass through a detecting
20 circuit 68 and amplifying it by means of an amplifier circuit 70.

FIG. 8 is a schematic perspective view of another embodiment of current detection unit. In FIG. 8, the components same as those of FIG. 3 are denoted
25 respectively by the same reference symbols. As shown in FIG. 8, the circuit substrate 30 that carries a magnetic detection device 10 is arranged so as to be

standing in parallel with the parallel electric wire sections and the magnetic detection device 10 is arranged on a prolonged line extending in the direction of arrangement of the parallel electric wire sections 32a, 32b. This arrangement operates
5 equally well so long as the magnetic field detecting direction is rectangular relative to the direction of arrangement the parallel electric wire sections 32a, 32b.

10 As described in detail above, according to the invention, it is possible to form a current sensor whose dimensions may not be increased when it is used for a large electric current by using a high sensitivity magnetic detection device. In short, it
15 is possible to realize a high sensitive compact current sensor. Additionally, since the magnetic detection device and the electric wire do not contact each other, they do not influence each other from the viewpoint of electric circuit so that the influence
20 of the impedance inserted to the current signal to be detected and the influence of other interferences are non-existent.

Still additionally, since no significantly large magnetic flux is generated, it is not necessary to
25 provide a large magnetic shield. Therefore, unlike conventional current detectors, magnetic saturation and other factors do not need to be considered for

the magnetic shield. Furthermore, unlike conventional
current detectors that comprise a magnetic core such
as a hall device, it is no longer necessary to care
about the problem of heat generation due to the
5 hysteresis loss of the core member.

Furthermore, current detection units can be
manufactured with a high productivity when the
magnetic detection device is mounted on a circuit
substrate and the reciprocal parallel electric wire
10 sections are made to run through a through hole or a
notch or when the substrate carrying the magnetic
detection device is arranged in parallel with the
electric current.